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An Overview Introduction of VSC-HVDC: State-of-art and Potential Applications in Electric Power Systems

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SUMMARY

High Voltage Direct Current (HVDC) seems going into another booming time since the first test line was developed by Dr. Uno Lamm about seventy years ago in Sweden. The boom of this time can be seen from not only fast increased project number but significant research interests around whole world as well. The major motivation behind comes from new challenges to the conventional ac grid, e.g. increased proportion of renewable power generation, flexibility requirements from power market, and environment impact. The new HVDC technology based on the Voltage Source Converter (VSC) is a feasible and attractive solution that can fulfil almost all above challenges due to its distinct advantages in the areas of controllability and flexibility, e.g. independent control of active and reactive power, fast control response speed, etc. Therefore, much effort is devoted to further extend its advantages and eliminate its drawbacks, such as high losses compared to Current Source Converter (CSC) HVDC and ac system. A new development milestone of VSC-HVDC technology and its application in the power system will be the South-West Link project in Sweden, which will start soon. It will be the first three-terminal VSC-HVDC links embedded in the grid, and marks the practical application of VSC-HVDC going into multi-terminal time.

This paper tries to follow and summary the important researches and development of VSC HVDC technology, especially in the VSC topology, modelling and control methods, and potential applications in the power system. All these researches will show profound and significant effects in the development of VSC-HVDC, and even on the future of electric power systems.

KEYWORDS

HVDC – CSC – VSC – Topology – Modelling – Control – Multi-terminal – Hybrid – Segment – DC grid

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1. Introduction

The traditional electric power system based on 3-phase ac transmission technology in general functions well and with good levels of availability and reliability. There are however challenges mainly arising from the increasing share of renewable generation, which will most likely increase the level of variability and unpredictability in electric power grid operation, increased needs for reserve power for power balancing, and will require more flexible power flow control. Other challenges include requirements from the electric power market, such as relieving transmission bottle necks, and the difficulties of obtaining new transmission corridors because of the environmental impact, especially in European and North American areas.

High Voltage Direct Current (HVDC), especially the Voltage Source Converter (VSC) HVDC, is a feasible and attractive technology to fulfil almost all above challenges, due to its distinct advantages in the areas of controllability and flexibility. The benefits from applying VSC-HVDC in the traditional ac grid include independent control of active and reactive power, very fast control response, using cable, ability to connect to weak system, black start ability, and facilitating the construction of multi-terminal system or even complete dc grids. An important new milestone of VSC-HVDC technology and its application in the power system will be the South-West Link project in Sweden, which will start soon. It will be the first three-terminal VSC-HVDC links embedded in the grid, and marks the practical application of VSC-HVDC going into multi-terminal time.

This paper gives an overall introduction of HVDC technology in Section 2, including basic theory of Current Source Converter (CSC) HVDC and VSC-HVDC and their comparisons. In Section 3 the state-of-art of recent VSC-HVDC researches is introduced, focusing on the new development of converter, modelling and control methods. Section 4 shows example projects and discusses the potential applications in the electric power system, the multi-terminal VSC-HVDC system, hybrid application of HVDC Classic and VSC, segment of AC grid by VSC-HVDC links, and DC grid.

2. HVDC basic: CSC and VSC

HVDC technology has been utilized in the electric power system for about sixty years since the first commercial link was put into operation between Sweden mainland and the island of Gotland in 1954. Today, it can be categorized in two types based on the switching devices employed in the converter, CSC-HVDC and VSC-HVDC,

CSC uses thyristor valves as switching devices. It is a kind of Line Commutated Converter (LCC) because thyristor can only be switched off when the current through it passes zero, therefore, it requires line voltage for commutation. CSC-HVDC is suitable for high voltage bulk power and long distance transmission projects without the effect of capacitance along the long transmission line. The typical examples are the Ultra HVDC (UHVDC) projects commissioned recently in China, which transmit about 6000MW power from hydro plants to the load area about 2000 km away through two overhead lines with ±800 kV dc voltage. Other applications include e.g. connection of two unsynchronized ac grids, or even grids with different system frequency. Figure 1 shows a 6-pulse converter based on thyristor and the typical bipolar HVDC system configuration.

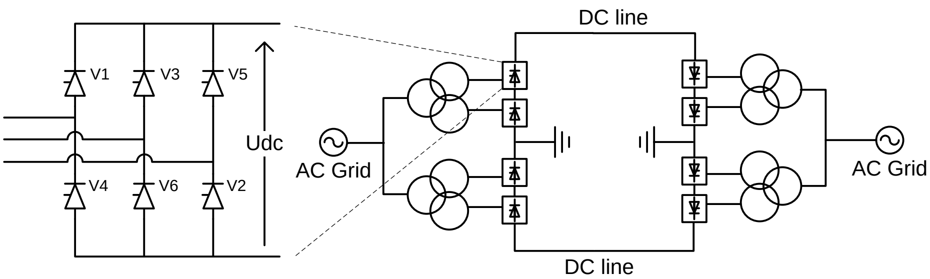

Figure 1 6-pulse valve (left) and bipolar configuration (right)

The first test VSC-HVDC system was constructed in 1997 in Hellsjön, Sweden. Then in 1999 in Gotland, Sweden, the first commercial VSC-HVDC project was put into operation. Since then, many projects have been constructed or are in planning for the near future. Today, Insulated Gate Bipolar

Transistor (IGBT) is commonly used with Pulse-Wide Modulation (PWM) control method in VSC-HVDC projects. A new VSC topology, Modular Multilevel Converter (MMC) using cascaded connection logic, is more attractive for applications in the grid because of its some unique features, e.g. the good sinusoidal waveform of the output voltage and low switching loss. Manufacturers have developed new generation of VSC on the basis of MMC, and applied in a practical project in USA. MMC will be described in details in Section 3. Being a forced-commutated voltage source converter, it does not need the ac voltage support from grid side for commutation. Meanwhile, by adopting PWM control method (or cascade connection method for MMC), it has very fast response speed, especially during the transient phase after disturbance. The key features of VSC-HVDC include the followings [1]:

- Independent control of both active and reactive power,
- Supply of passive networks and black-start capability,
- High dynamic performance,
- Multi-terminal possibility

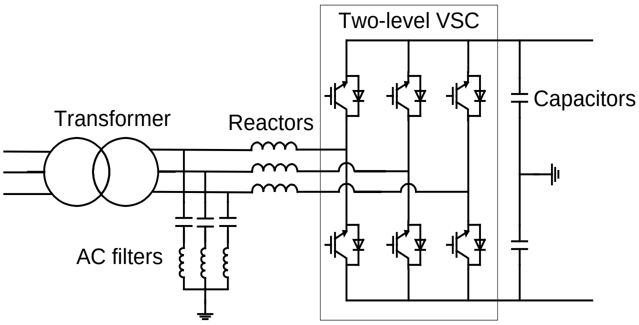

Figure 2 Typical configuration of VSC-HVDC with two-level converter.

The limits that block its application as replacement for CSC HVDC in the high voltage and bulk power transmission are mainly the present capacity limit of the IGBT itself. Higher losses compared with similar CSC due to the high switching frequency of PWM control is another well-known limiting factor. However, The power losses have been reduced to almost half value of the original level by employing new VSC topologies and modulation methods, and will be further reduced with the development of semiconductor [2]. So far, the maximum power of VSC-HVDC with bipole configuration can reach to 1200 MW with cables and 2400 MW with overhead lines [1]. The configuration of VSC-HVDC system using two-level VSC is shown in Figure 2.

3. State-of-the-art of VSC-HVDC technology

The detailed description of VSC-HVDC technology was reported in [2], including its basic theory, characteristics and performance. But it aims to general readers, like grid operators, investors, and anyone wanting to know VSC-HVDC. Here, a summary of recent important researches and development is presented, mainly focussing on the converter topologies, modelling and control methods, and extending its applications in the electric power system.

3.1. VSC topologies

The typical voltage source converter uses series-connected IGBTs as the switch device to share the high blocking voltage. Anti-parallel freewheeling diodes ensure four-quadrant operation of the converter. Capacitors on the dc side support the commutation and offer filtering for dc side harmonics.

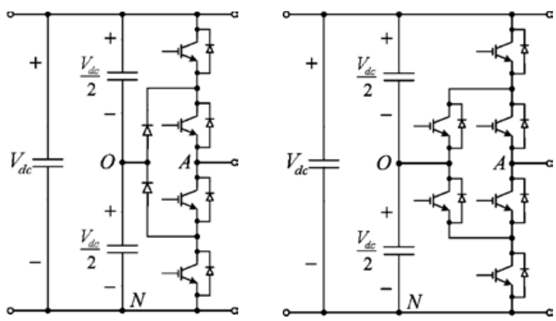

Figure 3 NPC (left) and ANPC (right).

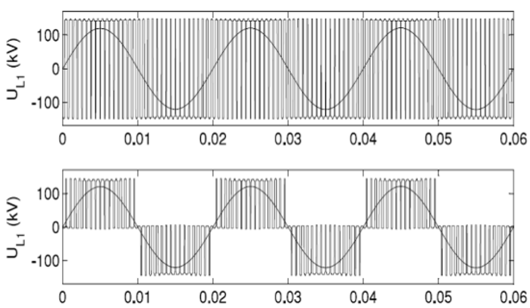

Figure 4 Line to neutral voltage of two-level (upper) and three-level (lower) converter.

Many VSC topologies are reported, especially multilevel topologies in [3]. Multilevel means that more than two voltage levels can be gained in one phase leg, which decreases the switching times of valve and makes the voltage wave form closer to sinusoidal curve. Topologies of a diode-clamped neutral-point-clamped three-level converter (NPC) [4] and an active NPC (ANPC) [5] are shown in Figure 3. Line to neutral voltage waveforms of both two-level and three-level converters with PWM are shown in Figure 4.

Although many VSC topologies has been developed, and show some attractive features theoretically, the commonly used converters in practical HVDC projects are still based on the two-level topology, or three-level converters in a few projects, as listed in Table 1. The main hindrances for multilevel converter application in HVDC projects lie in difficulties of balancing voltage across the dc capacitors, the uneven losses among devices, and increased complexity of control system. ANPC is an attractive solution for HVDC application since it can handle uneven loss distribution.

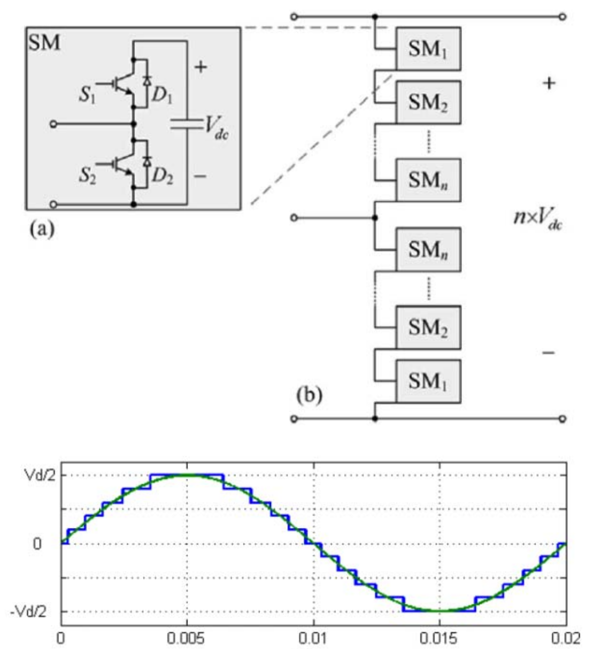

Figure 5 Upper: Modular multilevel converter topology [9], (a) Structure of one submodule (SM) and (b) Phase leg. Lower: ac line voltage waveform [6]

MMC using cascaded connection methods is paid high attention recently (see Figure 5) [6-8]. Compared to the other two types of converters, the difference is that there is not common capacitor of MMC connecting dc buses. The operation principle of MMC is that each switch module consisting of two valves can be switched in three modes as described below:

- S1 is turned on and S2 is turned off, the capacitor is inserted into the circuit. The module contributes with voltage to the phase voltage.
- S1 is turned off and S2 is turned on, the capacitor is bypassed.
- S1 and S2 are both turned off, the module is blocked when the capacitor voltage is higher than outside voltage.

MMC is attractive to the HVDC application, in contrast to two- or three-level converters, because cascaded connection method permits each module theoretically only needs to switch on and off only once per period, which greatly reduces the switching losses. The output waveform can be closely sinusoidal when the number of modules is large enough (usually more than 100 modules of each leg for HVDC application). This results in a very small harmonic content of the voltage, and means that the ac filter is not necessary any more in the HVDC stations.

3.2. Modelling and control

A large number of studies on the modelling and control of VSC-HVDC from different points of view can be found in e.g. [10-25]. Selection of VSC models in research depends on the time scope of the study. The voltage source model might be enough for the electromechanical transient study, while the detailed models using ideal switches will be necessary for the analysis in the electromagnetic transient level. Although various converter topologies are described in Section 2, it is important to keep in mind that no matter which topology is used, the VSC can always be treated as an equivalent ideal voltage source seen from the ac grid side after the ac filter. Control system of converter has the freedom to specify the magnitude, phase, and frequency of the produced sinusoidal voltage waveform. Certainly, the converter capacity

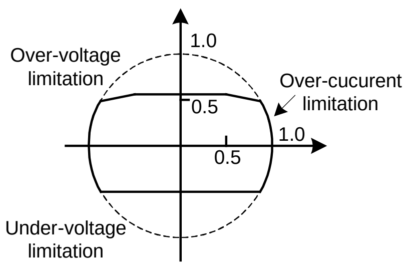

Figure 6 Operation area of VSC with limitations

limits shall be taken into account for control system design and stability study. Figure 6 shows the VSC operation area with capability limits.

Current controller is the core part of VSC control system and is usually categorized by hysteresis, linear PI, and deadbeat predictive regulators [16]. The linear PI controller based on the vector current control theory in synchronous d-q frame is often used in the 3-phase VSC control system because of its good performance [17], while a new proportional-resonant (PR) controller in stationary frame is reported in [16, 18] which does not need the d-q transformation and can enhance the converter reference tracking performance. Another novel controller, power-synchronization controller is introduced in [19, 20] and uses the internal synchronization mechanism of synchronous machines to synchronize the VSC with the ac grid. This new controller replaces the Phase Locked Loop (PLL) by a Power Synchronization Loop (PSL), and can overcome problems of vector current controller used in weak-ac-system connections. An unbalanced current control method is reported to work under unbalanced network condition in [21] by combining two controllers in both positive and negative d-q frames. The reference [14] studied the power-frequency control mode when a VSC is connected to an islanded network. For multi-terminal VSC-HVDC system, one more control section to ensure the right power sharing among VSCs is necessary. References [22] [23] proposed a method of dc voltage margin control to coordinate the dc power flow among VSCs in grid side, which is the counterpart of current margin control method in Classic HVDC system. A dc voltage droop control strategy is reported in [24] and [25] to achieve the same target.

4. Example of projects and potential applications

Present applications of VSC-HVDC mainly focus on the integration of offshore wind power, connection asynchronous grids, and cases in which cables have to be used. Table 1 shows the example of projects. These projects clearly show the development of VSC-HVDC technology. The power rating increases from less than 100MW to more than 1000MW, and the dc voltage level increases from about 10kV to 320 kV. All these improvements actually are corresponding to the update of the VSC topology and control method, from 2-level topology to multi-level, then MMC now.

Table 1. Example of VSC-HVDC projects

Project Name	Year of Commissioning	Power rating	Circuit Number	AC voltage	DC voltage	Length of DC line	Comments and reasons for choosing VSC-HVDC	Topology	Semi-contactors
Hellsjön, Sweden	1997	3 MW, ±3 MVAr	1	10 kV (both ends)	±10 kV	10km Overhead line	Test transmission. Synchronous AC grid.	2-level	IGBT
Gotland HVDC light, Sweden	1999	50 MW, -55 to +50 MVAr	1	80 kV (both ends)	±80 kV	2×70km Submarine Cable	Wind power (voltage support). Easy to get permission for underground cables.	2-level	IGBT
Eagle Pass, USA	2000	36 MW, ±36 MVAr	1	138 kV (both ends)	±15.9 kV	Back-to-back station	Controlled asynchronous connection for trading. Voltage control. Power exchange.	3-level	IGBT
Tjäreborg, Denmark	2000	8 MVA, 7.2 MW, -3 to +4 MVAr	1	10.5 kV (both ends)	±9 kV	2×4.3km Submarine cable	Wind power. Demonstration project. Normally synchronous AC grid with variable frequency control	2-level	IGBT
Terrenora Interconnection (Directlink), Australia	2000	180 MW, -165 to +90 MVAr	3	110 kV –Bungalora 132 - kV Mullumbimby	±80 kV	6×59km Underground cable	Energy trade, Asynchronous AC grid. Easy to get permission for underground cables	2-level	IGBT
MurrayLink, Australia	2002	220 MW, -150 to +140 MVAr	1	132 kV - Berri 220 kV – Red Cliffs	±150 kV	2×180km Underground cable	Controlled asynchronous connection for trading. Easy to get permission for underground cables	3-level ANPC	IGBT
CrossSound, USA	2002	330 MW, ±150 MVAr	1	345 kv–NewHeaven 138 kV - Shoreham	±150 kV	2×40km Submarine cable	Controlled asynchronous connection for power exchange. Submarine cables	3-level ANPC	IGBT
Troll A offshore, Norway	2005	84 MW, -20 to +24 MVAr	2	132 kV - kollsnes 56 kV - Troll	±60 kV	4×70km Submarine cable	Environment, CO_2 tax. Long submarine cable distance. Compactness of converter on platform electrification.	2-level	IGBT
Estlink, Estonia-Finland	2006	350 MW, ±125 MVAr	1	330 kV – Estonia 400 kV - Finland	±150 kV	2×31km Underground 2×74 km Submarine	Length of land cable, sea crossing and asynchronous AC systems	2-level	IGBT

NORD E.ON 1, Germany	2009	400 MW	1	380 kV – Diele 170 kV – Borkum 2	±150 kV	2×75km Underground 2×128 km Submarine	Offshore wind farm to shore. Length of land and sea cables. Asynchronous system.		IGBT
Caprivi Link, Namibia	2009	300 MW	1	330 kV – Zambezi 400 kV – Gerus	350 kV	970 km Overhead line	Synchronous AC grids. Long distance overhead line, connecting two weak networks		IGBT
Valhall offshore, Norway	2009	78 MW	1	300 kV – Lista 11 kV – Valhall	150 kV	292 km Submarine coaxial cable	Reduce cost and improve operation efficiency of the field. Minimize emission of green house gases	2-level	IGBT
Trans Bay Cable, USA	2010	400 MW, ±170 MVAr	1	230kV- Pittsburg 138 kV - San Francisco	±200 kV	88 km Submarine cable	Provide reliable energy to San Francisco without having to install a power generation plant.	MMC	IGBT
BorWin2, Germany	2013 (scheduled)	800MW		150kV-offshore, 400kV - Diele	300 kV	125km offshore, 75km onshore	Two offshore wind farms to onshore. Capacity of VSC-HVDC	MMC	IGBT
HelWin1, Germany	2013 (scheduled))	576MW		155kV-offshore, 259-Büttle	250 kV	130km	Integrate offshore wind farms to onshore grid.	MMC	IGBT
INELFE	2013 (scheduled)	2×1000 MW	2	400kV- Baixas, France 400kV-Santa Llogaia, Spain	±320 kV	4×(32km Span + 33km France) underground cable	Transport large amount of electric power with a minimum of transmission losses	MMC	IGBT
South West link	South part 2014 West part 2016 (Scheduled)	South part: 2×600 MW	2	400 kV	±300 kV	South part: 4×180km underground cable + 70km overhead line	The first three-terminal VSC-HVDC links, high transmission capacity		

Note: project information before 2010 is extracted from [9]

4.1. Multi-terminal VSC-HVDC

It is easier to build a multi-terminal dc system with VSC-HVDC than CSC-HVDC, because dc power flow direction is changed by changing the direction of dc current and keeping dc voltage constant in a VSC-HVDC system. Many relevant studies have been reported, some of which are [24-39]. Studies in [24-34] identified the advantages of using multi-terminal VSC-HVDC to integrate large offshore wind farms. Figure 7 shows a typical configuration of multi-terminal dc system connecting to wind farms. Studies in [35-38] suggested an alternative solution of feeding power to the load centres of big cities using multi-terminal VSC-HVDC system. The single line diagram is shown in Figure 8. Reference [39] studies the application of multi-terminal VSC-HVDC in the transmission level and indicates that multi-terminal configuration is a feasible alternative for ac network reinforcement to fully exploit the economic and technical advantages of VSC-HVDC technology. As mentioned above, South-West link will be the first multi-terminal VSC-HVDC project around whole world which will reinforce the Nordic system by improving the transmission capacity from north to south in Sweden and alleviating the bottlenecks between Norway and south coast of Sweden. It will prove the advantages of VSC technology in grid reinforcement, and will certainly attract more research interests in the operation level of VSC-HVDC embedded in power grid.

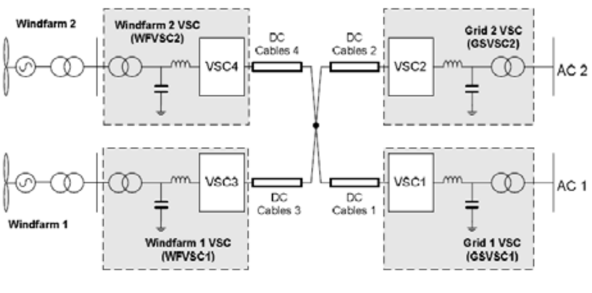

Figure 7 Multi-terminal VSC-HVDC system connecting to offshore wind farm [24]

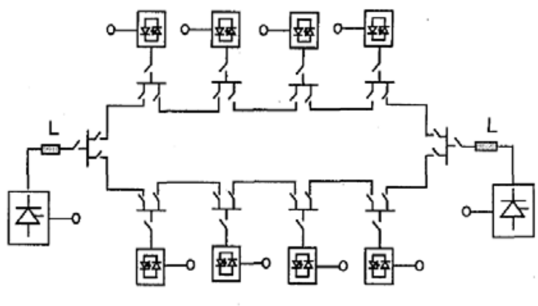

Figure 8 Multi-terminal VSC-HVDC system using in urban area [35]

4.2. Hybrid application of CSC and VSC

Some studies trying to combine the advantages of both CSC and VSC are reported in [40-45]. A hybrid system comprising Classic-HVDC and VSC working as STATCOM is proposed in [40] to connect an island network without generation capabilities, Figure 9. The hybrid system was shown to lead to both low capital cost and power loss of CSC and the fast dynamic performance of VSC system.

4.3. Segmentation of ac grid

A kind of dc segmented grid was studied in [46] to limit the effect of disturbance to the power grid where the whole ac network is decomposed into sections and connected via VSC-HVDC links. VSC-HVDC plays a role as “Firewall” against the spreading of disturbance around the whole network. Figure 10

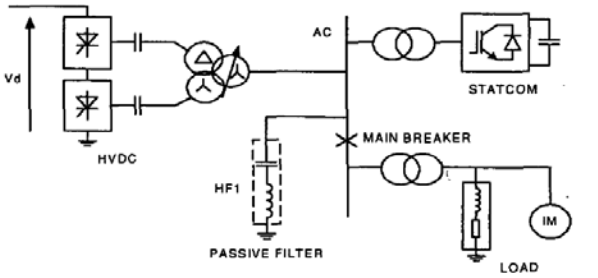

Figure 9 Hybrid HVDC system supplying an island load [40]

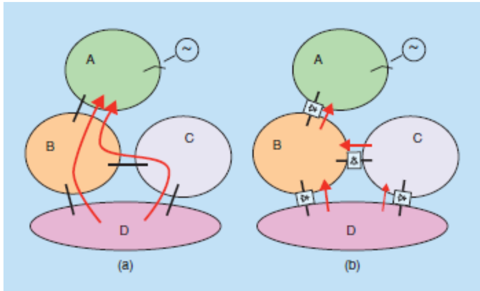

Figure 10 (a) interconnected by tie lines, (b) interconnected by VSC-HVDC links [46]

4.4. Dc grid

Further development of HVDC systems may result in the emergence of dc grid in the transmission level. Reference [47] indicated that the dc networks could differ from multi-terminal HVDC by the possibility to employ multiple dc voltage levels, and studied principles of developing dc transmission grids based on high power dc/dc converters. Research reported in [48, 49] studied the feasibility and efficiency of dc network in LV and MV level. Dc network is also an attractive solution for interconnection of wind turbines within offshore wind farms. A dc offshore grid based on resonant dc-dc converters was studied in [50].

5. Conclusions

In this paper, an overview of state-of-art of VSC HVDC technology is introduced. The most important development of VSC technology recently is the application of MMC in HVDC field. It not only further enhances the advantage of VSC-HVDC, such as the fast dynamic response, independent active and reactive power control, and ability of connecting to “black” network, but also eliminates some well known drawbacks, like high switching losses and harmonics. Some other improvements, like increase of SVC capacity and various new control methods, also expands VSC applications in the power grid. Multi-terminal VSC-HVDC is another significant improvement from the application point of view. The natural idea of connecting dc links together to form the multi-terminal VSC-HVDC system will quite possibly lead to the emergence of dc grids, which may profoundly affect the future of the electric power grid.

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